

PATENT
Atty. Dkt. M03A224

EXPRESS MAIL MAILING LABEL: EK603122764US

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

NEW PATENT APPLICATION

MONOLITH BASED CATALYTIC PARTIAL OXIDATION PROCESS FOR
SYNGAS PRODUCTION

Inventors: Weibin Jiang, Seungdoo Park, Mark S. Tomczak, Divyanshu R. Acharya, Satish S. Tamhankar, Ramakrishnan Ramachandran

MONOLITH BASED CATALYTIC PARTIAL OXIDATION PROCESS FOR
SYNGAS PRODUCTION

This application claims priority from Provisional US Patent Application
5 60/436,074 filed December 23, 2002.

BACKGROUND OF THE INVENTION

The conversion of hydrocarbons to hydrogen and carbon monoxide
10 containing gases is well known in the art. Examples of such processes include
catalytic steam reforming, auto-thermal catalytic reforming, catalytic partial
oxidation and non-catalytic partial oxidation. Each of these processes has
advantages and disadvantages and produces various ratios of hydrogen and
carbon monoxide, also known as synthesis gas. The present invention is
15 directed to a catalytic partial oxidation process.

Partial oxidation processes are also well known and the art is replete
with various catalytic partial oxidation processes. Partial oxidation is an
exothermic reaction wherein a hydrocarbon gas, such as methane, and an
20 oxygen-containing gas, such as air, is contacted with a catalyst at elevated
temperatures to produce a reaction product containing high concentrations of
hydrogen and carbon monoxide. The catalysts used in these processes are
typically noble metals, such as platinum or rhodium, and other transition metals,
such as nickel on a suitable support.

25 Partial oxidation processes convert hydrocarbon-containing gases, such
as natural gas, to hydrogen, carbon monoxide and other trace components
such as carbon dioxide and water. The process is typically carried out by
injecting preheated hydrocarbons and an oxygen-containing gas into a
30 combustion chamber where oxidation of the hydrocarbons occurs with less than
stoichiometric amounts of oxygen for complete combustion. This reaction is
conducted at very high temperatures, such as in excess of 700°C and often in

excess of 1,000° C, and pressures up to 150 atmospheres. In some reactions, steam or carbon dioxide can also be injected into the combustion chamber to modify the synthesis gas product and to adjust the ratio of hydrogen to carbon monoxide.

5

More recently, partial oxidation processes have been disclosed in which the hydrocarbon gas is contacted with the oxygen-containing gas at high space velocities in the presence of a catalyst such as a metal deposited on a ceramic foam (monolith) support. The monolith supports are impregnated with a noble 10 metal such as platinum, palladium or rhodium, or other transition metals such as nickel, cobalt, chromium and the like. Typically, these monolith supports are prepared from solid refractory or ceramic materials such as alumina, zirconia, magnesia and the like. During operation of these reactions, the hydrocarbon feed gases and oxygen-containing gases are initially contacted with the metal 15 catalyst at temperatures in excess of 400°C, typically in excess of 600°C, and at a standard gas hourly space velocity (GHSV) of over 100,000 per hour.

SUMMARY OF THE INVENTION

20 The present invention provides an improved process for the catalytic partial oxidation of hydrocarbons to produce hydrogen and carbon monoxide and less than ~2% carbon dioxide. Accordingly, the process permits the reaction to be initiated at room temperature, thereby reducing operating and capital costs. The inventive process employs a metal catalyst deposited on a 25 ceria-coated zirconia monolith support, which exhibits high conversions of hydrocarbons to synthesis gas.

In one aspect, the invention provides a process for the partial oxidation of hydrocarbons to produce hydrogen and carbon monoxide comprising 30 contacting a mixture of a hydrocarbon-containing feed gas and an oxygen-containing feed gas with a catalytically effective amount of a reduced metal catalyst consisting essentially of a transition metal selected from the group of

nickel, cobalt, iron, platinum, palladium, iridium, rhenium, ruthenium, rhodium, osmium and combinations thereof, supported on or in a ceria-coated zirconia monolith support, at a pressure of between 1 and 20 atmospheres, a feed gas standard gas hourly space velocity of about 50,000 to about 500,000 per hour, 5 and a linear velocity of about 0.2 to 2.0 meter per second (m/s).

In another aspect, this invention provides a process for the partial oxidation of hydrocarbons to produce hydrogen and carbon monoxide, which can be initiated at a temperature of about and above 10° C by contacting the 10 said catalyst with the feed mixture along with injection of a small amount of H₂. In another embodiment of the present invention, reaction can also be initiated at room temperature by adding a small amount of hydrogen to feed mixture in the presence of continuous CO₂ flow in order to achieve a gradual increase in catalyst temperature to avoid thermal shock.

15

In a preferred embodiment the present invention provides for a method for producing carbon monoxide and hydrogen comprising contacting a hydrocarbon-containing gas and an oxygen-containing gas with a reduced metal catalyst supported by a ceria-coated zirconia monolith.

20

In another preferred embodiment, the present invention provides for a method for producing carbon monoxide and hydrogen comprising contacting a hydrocarbon-containing gas and an oxygen-containing gas in the presence of hydrogen gas with a reduced metal catalyst supported by a ceria-coated 25 zirconia monolith.

An additional embodiment of the present invention is a reactor comprising a vessel, at least one ceramic foam disk impregnated with a catalytic material and at least one blank ceramic foam disk.

30

A further embodiment of the present invention is a method for producing carbon monoxide and hydrogen comprising contacting a

hydrocarbon-containing gas, carbon dioxide, and an oxygen-containing gas with a reduced metal catalyst supported by a ceria-coated zirconia monolith.

In another embodiment of the present invention, hydrogen addition to
5 the feed gas mixture of natural gas and oxygen is maintained at all times
during the production of carbon monoxide and hydrogen to ensure that the
catalyst remains in the reduced form.

BRIEF DESCRIPTION OF THE DRAWINGS

10

Fig. 1 is a schematic representation of a reactor that is employed in the
present invention.

15

Fig. 2 is a schematic representation of a process for producing carbon
monoxide and hydrogen while employing continual addition of hydrogen to
the feed gases.

20

Fig. 3 is a schematic representation of a process for producing carbon
monoxide and hydrogen while employing continual addition of hydrogen to
the feed gases.

25

Fig. 4 is a schematic representation of a graph of flowrate and
temperature versus time for a start-up procedure while employing injection of
hydrogen with continuous carbon dioxide flow in the feed mixture.

25

Fig. 5A is a graph detailing methane conversion versus percentage
carbon dioxide in feed.

30

Fig. 5B is a graph detailing carbon dioxide conversion versus
percentage carbon dioxide in feed.

DETAILED DESCRIPTION OF THE INVENTION

Natural gas and an oxygen-containing gas are mixed through lines 1 and 2 in a simple mixing device 3, with velocity exceeding the natural gas flame 5 velocity so as to avoid flammability. The C/O₂ ratio in the mixture is in the range 1.5 to 2.0, preferably in the range 1.6 to 1.9. Optionally, steam or CO₂ is added to natural gas to adjust the H₂/CO ratio in the product. Optionally, natural gas may be preheated by exchanging heat with the hot product stream or by other means so that the feed mixture temperature reaches about 80 °C or even 10 higher. Since partial oxidation reaction is highly exothermic, the reactor is designed as a refractory-lined vessel 4 to achieve good thermal insulation. The monolith catalyst 6 is located at the bottom, carefully sealed with zirconia 15 cement to prevent leakage of any unreacted feed gas. The top space is then filled with inert blank foam monolith disks 5 to improve the flow distribution and to avoid flammability. A gas distribution means such as a stainless steel 20 distribution plate may be placed between the blank ceramic foam monoliths.

One key aspect of the invention is that the partial oxidation reaction is carried out at pressures in the range of about 1.0 bar to about 10.0 bar and 20 preferably about 1.5 bar to about 3.0 bar. By employing this pressure range, carbon formation is completely avoided and addition of steam to prevent carbon formation is not necessary as would be the case for high pressure operation. The main benefit of running the reaction without steam is that the 25 syngas produced has 2:1 H₂ to CO ratio which is critical for many applications of syngas. Since the reaction is at comparatively lower pressure, the product syngas is compressed to the desired pressure after cooling.

The metal catalysts employed in the present invention consist of a 30 ceramic monolith support structure composed of ceria coated on zirconia substrate and coated or impregnated with a transition metal or combinations thereof. As used herein, "metal catalyst" refers to the entire catalyst structure including the metal and the monolith support. The monolith support is generally

a ceramic foam-like structure formed from a single structural unit wherein the passages are disposed in either an irregular or regular pattern with spacing between adjacent passages. The single structural unit is used in place of conventional particulate or granular catalysts, which are less desirable in the 5 present process. Examples of such irregularly patterned monolith supports include filters used for molten metals. Examples of regularly patterned supports include monolith honeycomb supports used for purifying exhausts from motor vehicles and used in various chemical processes. Preferred are the ceramic foam structures having irregular passages. Both types of monolith supports are 10 well known and commercially available.

The catalyst element consists of a ceramic foam monolith composed substantially of zirconia, coated with about 15~20 wt. % ceria providing surface area for the metal impregnation, and contains 0.5~5 wt. % noble metal, 15 preferably rhodium in metallic form, more preferably about 2 wt. % Rh. Optionally, a transition metal, such as Ni at 2~4 wt. % may be used by itself or in combination with Rh. The reactor contains several ceramic foam disks including those with catalyst impregnated on them and the remaining blanks to fill the void space. The blanks can be made of alumina, zirconia, cordierite or 20 mixtures thereof. The impregnated metal (Rh), synergistically with ceria, acts as catalyst for the partial oxidation process. The disks with catalyst have porosity in the range 40 to 70 pores per inch (ppi) to maximize catalyst loading. On the other hand, blank disks have a relatively high porosity 20 to 40 ppi in order to keep the pressure drop low. The dimensions, i.e. diameter and height, are 25 selected to meet two criteria, namely feed gas space velocity in the range of about 50,000~500,000 per hour (expressed as hourly standard volumetric feed flow rate per unit volume of the catalytic monolith), and linear velocity on a similar basis (standard conditions) of about 0.2 to 2 m/s.

30 On the catalyst surface hydrocarbons and oxygen in the feed mixture react rapidly to produce H₂ and CO, along with traces of CO₂ and H₂O and unreacted methane, as well as heat due to the exothermic nature of the

reaction. The hot synthesis gas ($H_2 + CO$) 8 is quickly cooled by quenching water 7 to produce steam and to prevent carbon formation. The reactor design shown in Figure 1 includes a quench system which allows cooling of syngas as it exits the monolith catalyst. The quenching system is designed to permit 5 several modes of operation. For example,

- Minimum quench mode allows maximum heat recovery from syngas by quenching the syngas to a temperature which reduces carbon formation tendency.
- Maximum quench mode allows syngas to be cooled down to 100 to 150 °C 10 which represents a low capital cost solution if heat recovery is not desired.
- Partial quench mode allows the syngas to be cooled down to temperatures suitable for downstream processing, e.g. water-gas shift reaction to convert majority of the CO to H_2 .

15 As mentioned above, the metal catalyst is a singular unit of varying dimensions depending on the size and design of the reactor. In a preferred embodiment, the reactor is a pipe or tube of suitable material and construction having a diameter of between about 1 and 100 inches. The feed gas mixture is fed into one end and the partial oxidation reaction occurs on the metal catalyst 20 with the product gas exiting from the other end. The metal catalyst can also be comprised of multiple monolith units to form an assembly of units disposed in end-to-end arrangements. It is preferred that the metal catalyst has porosity and orientation, which minimize the pressure drop of the feed gas through the catalyst. Moreover, multiple individual reactors can be used to form an 25 assembly of reactors disposed in a side-by-side arrangement for increased production. For example, multiple pipes or tubes can be packed together as an assembly to form a single reactor unit with each individual pipe containing the metal catalyst.

30 A significant drawback of all of the earlier partial oxidation processes is that they require an external source of heat to initiate the partial oxidation

reaction, or require a separate pre-heat step involving a chemical reaction. As stated above, the partial oxidation reaction is exothermic and once the reaction is started, the heat of the reaction will maintain the elevated temperature without the addition of external heat energy. However, since the process

5 requires temperatures in excess of 400° C to start or initiate the reaction, an external heat source or other means are still required. Of course, this requires additional capital costs and adds engineering complexities to the process thereby reducing its commercial attractiveness. To attempt to address this issue, some prior art processes have employed special initiating compounds to

10 decrease the initiation temperature. For example, U.S. Patent No. 4,879,253 discloses the use of methanol as an initiating compound to reduce the initiating temperature in the range of 100° to 500° C. U.S. Patent No. 6,458,334 B1 discloses the use of ceria-based monolith support to lower the initiation temperature to as low as ~100 °C, without the addition of any initiation

15 compound.

The present invention provides an improved partial oxidation process in which the initiation temperature can be as low as about 10° C. The present process eliminates the need for an external heat source or a separate pre-heat

20 step to initiate the reaction thereby increasing the commercial attractiveness of the process. The inventive process involves controlled addition of hydrogen in the feed mixture while maintaining a proper sequence of introducing the various gas components in the feed mixture to achieve room temperature startup of this invention.

25 Furthermore it was discovered that the startup at room temperature (above 10 °C) using small amount of H₂ is possible only with the use of ceria-coating on the base monolith support, including metal and ceramic monoliths such as stainless steel, zirconia, titania etc. Tests show that room temperature

30 start up is impossible using small amount of H₂ with, for example, a zirconia supported catalyst, without ceria coating, as described in Example 1. The preferred operating procedure of the inventive process is as described below:

1. Natural gas is first introduced at the desired flow rate.
2. Once the natural gas flow reaches its desired set point, hydrogen injection begins. This is critical from safety point of view and to maintain natural gas rich conditions before oxygen is added.
- 5 3. Oxygen flow is then started.
4. The H₂ flow, typically about 0.5 to 4% of the total flow, is maintained for 10 to 30 seconds.
5. Startup of the reaction is indicated by the rapid increase in the catalyst temperature to >400 °C. The startup can occur before the oxygen flow has
- 10 reached its set point demonstrating that only a short injection time of hydrogen is necessary.

It must be emphasized here that injection of hydrogen is not an additional step. In reality, hydrogen injection takes place between the introduction of natural gas and oxygen flows. For example, if hydrogen injection is not desired then there is no change in the way natural gas and oxygen are mixed and introduced to the reactor.

Furthermore, the startup at room temperature is also possible with continuous flow of CO₂ as reactant in the feed mixture. Shown as Figure 4, The preferred operating procedure of the inventive process is as described below:

1. Natural gas and carbon dioxide are first introduced at the desired flow rate
2. Once the natural gas and carbon dioxide flows reach their desired set points, hydrogen injection begins.
- 25 3. Oxygen flow is then started.
4. The H₂ flow, typically about 0.5 to 4% of the total flow, is maintained for 10 to 30 seconds.
5. Startup of the reaction is indicated by the rapid increase in the catalyst temperature to >400 °C.

30

It should be pointed out that addition of CO₂ effectively controls the front temperature of catalyst as well as controls the heat-up rate of the catalyst bed.

Therefore the initial thermal shock on monolith catalyst can be avoided through this method.

Alternatively, the present invention provides for a process whereby 5 hydrogen is continually fed to the feed gas mixture of natural gas and oxygen. To maintain optimum efficiency in the process, the monolith catalyst needs to be in a reduced state. During startups, shutdowns and upset conditions, the monolith catalyst can become exposed to oxygen which can deactivate the monolith catalyst, particularly when the catalyst is hot. By ensuring a 10 continuous feed of hydrogen to the gas feed mixture, the monolith catalyst remains in the reduced form and maintains its catalytic activity.

The present invention provides for two methods by which hydrogen is continuously fed to the feed gas mixture. The first uses a hydrogen-rich 15 stream which exits either from the carbon monoxide pressure swing adsorption unit or cold box. The second method utilizes product syngas after heat recovery and cooling.

As described in Fig. 2, a schematic process for the production of 20 hydrogen and carbon monoxide is depicted. Lines 10 and 12 connect to feed mixer A and deliver oxygen and natural gas respectively. Line 11 delivers hydrogen to the feed mixer A and is used in the embodiments of the invention where hydrogen is injected during the startup process.

25 Line 14 exits the feed mixer A and delivers oxygen, hydrogen and natural gas to the monolith reactor B where the monolith catalyst is housed. The monolith catalyst is the ceramic monolith support structure composed of ceria coated on zirconia substrate and coated or impregnated with a transition metal or combinations thereof. The partial oxidation process occurs therein 30 and the resulting product gas stream, primarily carbon monoxide and hydrogen, are delivered through line 16 to the cold box or carbon monoxide pressure swing adsorption unit C whereby carbon monoxide is separated

from the product gas stream. Product carbon monoxide leaves via line 18 and the remaining portion of the product gas leaves through line 20 to hydrogen pressure swing adsorption unit D where hydrogen is separated from the product gas and leaves via line 22.

5

In the inventive embodiment for using hydrogen recycle depicted here, the product gas exiting the cold box or carbon monoxide pressure swing adsorption unit C is hydrogen rich and part of this stream is diverted at valve 21 and directed along line 23 to the feed mixer A. This flow of hydrogen-rich gas can be continuously diverted from the cold box or carbon monoxide pressure swing adsorption unit C during the production process, thereby achieving a steady state whereby hydrogen is continuously present in the feed gas mix.

15

Alternatively as depicted in Fig. 3, rather than having valve 21 divert hydrogen-rich gas through line 23 to the feed mixer A, a valve 25 is placed in line 16. This valve connects with line 27 which connects to feed mixer A. This embodiment diverts product gas, containing primarily carbon monoxide and hydrogen, through valve 25 and line 27, back to the feed mixer A whereby hydrogen will continuously mix with the feed gas as long as the partial oxidation is occurring. This also achieves a steady state presence of hydrogen in the feed gas mixture.

20

U.S. Patent No. 6,458,334 B1 teaches the use a mixture of air and a small amount of H₂, introduced at a gas hourly space velocity of 4000 to 10,000 per hour, to achieve heating of the catalyst as well as its reduction in a separate step prior to starting the process feed flow. US Patent 6,329,434 B1 discloses a method to initiate the partial oxidation process by first introducing a H₂/O₂ mixture with or without a diluent, which is pre-heated preferably to 50 to 300° C. The mixture reacts on the catalyst and raises the catalyst temperature to a temperature at which hydrocarbon-oxygen partial oxidation reaction can be initiated.

The method of the present invention is unique in that the hydrocarbon-oxygen mixture is fed to the reactor at room temperature, and a small amount of H₂ is injected for a short time to initiate the partial oxidation reaction. We
5 have also found that injection of hydrogen on its own is not enough to achieve room temperature start-up. The room temperature start-up can only be achieved by hydrogen injection combined with correct sequence of introducing natural gas and oxygen. Startup at room temperature (above 10 °C) using a small amount of H₂ is possible primarily by the use of ceria-coating on the base
10 monolith support, including metal and ceramic monoliths such as stainless steel, zirconia, titania etc. Furthermore, the timing, amount and ensuring safety are critical parts of hydrogen injection as practiced in this invention. Thus, a further improvement is achieved in the startup procedure.

15 To shut down the reactor, N₂ flow is first started through the reactor, O₂ in the feed is then turned off, and the natural gas flow is turned off last. Proper care is taken to ascertain that no flammable or carbon formation conditions exist within the system. It is important to make sure that oxygen is not present in the reactor when there is no natural gas flow during shut-down in order to
20 prevent oxidation of the catalyst which, if occurs, will deactivate the catalyst.

Another embodiment of the present invention is a process for the partial oxidation of hydrocarbons such as methane (natural gas) by contacting a feed containing the hydrocarbon, O₂ and CO₂ through a catalyst comprising rhodium supported on a ceria-coated monolith. The presence of CO₂ leads to convert some product H₂ from partial oxidation reaction to CO. Such a reaction will significantly increase CO production. Addition of CO₂ also increases the operating window for partial oxidation in terms of flammability. The conversion of CO₂ can be further improved by preheating the feed mixture to a higher
25 temperature. It was found that addition of up to about 30 volume % CO₂ causes no significant deterioration in performance, and indeed, about 30% conversion of CO₂ is achieved in the short contact time reactor of this invention.
30

The key aspect again is the low-pressure operation, which helps prevent carbon formation under these conditions.

It has also been observed that, when using the inventive process, the
5 conversion of methane to hydrogen and carbon monoxide depends on both,
space velocity and linear velocity at a fixed carbon to oxygen ratio in the feed.
Most importantly, multiple layers of catalyst monoliths not only allow higher
throughput capability at the same space velocity but also give better methane
conversion at the same linear velocity. Example 2 illustrates the effect of layers
10 of monoliths on the process performance.

The following examples illustrate the improved partial oxidation process
of the present invention.

15 EXAMPLE 1

A zirconia monolith having 45 pores per inch, 0.7 inch in diameter and
0.39 inch long, was first coated with 20 wt. % ceria and then impregnated with 2
% by weight of rhodium metal to prepare the metal catalyst. Detailed
20 preparation method can be found in co-pending US patent application Serial
Number 10/143,705. The reactor containing the metal catalyst monolith was
purged with nitrogen gas at 10° C for 60 minutes.

Methane was first introduced at a flow rate of 8.8 slpm. A small amount
25 of H₂ (0.5 slpm) was injected into the methane line for up to 30 seconds. At
the same time, O₂ flow was started and adjusted to obtain the desired C/O₂
ratio of 1.75. Startup of the reaction was indicated by the rapid increase in the
catalyst temperature to >800 °C within a few seconds with the production of
hydrogen and carbon monoxide. Therefore only about 4% H₂ in feed mixture is
30 required for only 30 seconds to start up the partial oxidation of methane.

Comparative Example A

A metal catalyst was prepared as described in Example 1. The same amount of rhodium metal was loaded on the ceria-coated zirconia support.

5

A premixed gas mixture containing methane (8.8 slpm), oxygen (5.0 slpm) and hydrogen (0.5 slpm) was passed into the reactor containing the metal catalyst at 10° C. The reaction could not be initiated until hydrogen amount was increased to 22 mol % (3 slpm). This shows the importance of the 10 sequence of addition of different gases in the feed mixture.

10

Comparative Example B

A metal catalyst was prepared as described in Example 1, except that 15 the monolith support was made of zirconia. The same amount of rhodium metal was loaded on the zirconia support, without any ceria coating as described in Example 1.

When attempting to start the reaction by following the procedures 20 described in Example 1 using hydrogen injection, the reaction could not be initiated until a temperature of about 150° C was reached. This clearly shows the synergistic role played by ceria.

Example 2

25

To compare the effect of linear velocity and space velocity, monolith catalysts, as described in Example 1, of two different diameters (0.7" and 1") were used. To compare results on the same catalyst volume basis, data with four stacked catalyst disks of 0.7" diameter x 0.39" thickness are compared to 30 those with two 1"x 0.39" monolith catalysts. A feed mixture containing 64% methane and 36% oxygen was passed through the reactor, following the same start up procedure as in Example 1. Here space velocity is defined as total feed

gas flow rate divided by the catalytic monolith volume and linear velocity is defined as total feed gas flow rate divided by the cross-sectional area of the catalytic monolith. Table 1 shows that, for the same space velocity and at the same reaction conditions, increasing linear velocity will increase methane conversion with better H₂ and CO selectivity. On the other hand, for the same linear velocity, lower space velocity results in better methane conversion and appreciably less methane slip. In other words, increasing L/D aspect ratio of catalytic monolith improved performance of partial oxidation reaction.

10 **Table 1**

2% Rh on 20% CeO ₂ coated ZrO ₂ monolith	Space Velocity	Linear Velocity	Conversion %	Selectivity %	
	(1/hr)	(m/s)	CH4	H2	CO
4 x 0.7" x 0.39"	86036	0.87	97.8	95.8	93.9
2 x 1" x 0.39"	85810	0.47	97.0	96.0	92.0
2 x 1" x 0.39"	158464	0.87	95.6	95.0	93.2
4 x 0.7" x 0.39"	138817	1.40	99.0	96.7	93.7
2 x 1" x 0.39"	138731	0.76	97.2	95.3	93.2

EXAMPLE 3

15 A partial oxidation reaction was initiated following the same procedure as described in Example 1 with the same metal catalyst, which was used in Example 1. A gaseous mixture containing methane and oxygen at carbon to oxygen ratio of 1.75 and between 0 to about 30% by volume of carbon dioxide was then fed to the reactor containing the monolith catalyst. This mixture was different from the mixture which was used to initiate the reaction. This feed mixture was fed at a space velocity of 150,000 hr⁻¹. The reaction temperature decreased from 1020° to 750° C due to endothermic reverse gas shift reaction. The typical product gas contained 39% hydrogen, 33% carbon monoxide, 13.1% carbon dioxide, 1.3% methane and 12.6% water. The conversion rate of methane and carbon dioxide were calculated from the measured concentrations in the product. The results are shown in Figures 5a and 5b

below. When feed gas mixture was preheated to 300 °C, there is a slight increase in both CH₄ and CO₂ conversion. The conversion measurements were calculated through element material balance

5 While this invention has been described with respect to particular embodiments thereof, it is apparent that numerous other forms and modifications of this invention will be obvious to those skilled in the art. The appended claims and this invention generally should be construed to cover all such obvious forms and modifications which are within the true spirit and
10 scope of the present invention.